APPLICATION OF BMDO IS&T DISTRIBUTED COMPUTING AND SIMULATION RESEARCH TO BM/C^3 SYSTEMS

Stan M. Smith
US Army Space and Missile Defense Command
PO Box: 1500, Attn: SMDC-TC-AP
Huntsville, AL 35807
smithsm@smdc.army.mil

John K. McFee, Jr.
The MITRE Corporation
1500 Perimeter Parkway, Suite 310
Huntsville, AL 35806
jmcfee@mitre.org

James C. Hayes
COLSA Corporation
6726 Odyssey Drive
Huntsville, AL 35806
jhayes@colsa.com

Maura Young Weise
COLSA Corporation
6726 Odyssey Drive
Huntsville, AL 35806
mweise@colsa.com

19981110 075

Abstract

The Ballistic Missile Defense Organization (BMDO) Innovative Science and Technology (IS&T) Program sponsors research which is advancing the current state-of-the-art in parallel discrete event simulation (PDES), high speed communications, distributed computing architectures, and automated decision support. This paper examines the application of these technologies to Theater Missile Defense (TMD) and National Missile Defense (NMD) Battle Management/Command Control and Communications (BM/C^3) applications including real-time battle planning and faster-than-real-time defense evaluation. The requirement for performing faster-than-real-time defense evaluation in future BM/C^3 systems is derived from the understanding that a real-time defense planning capability will require a faster-than-real-time defense evaluation capability. This capability will require a mechanism for executing potentially hundreds of full-scale system simulations with various threats, configurations, and resources in a sufficiently short amount of time that results can be evaluated and provided to the decision-maker enabling more effective decision-making on the battlefield. Research results are described demonstrating relevance of optimistic computing technology to performing faster-than-real-time defense evaluation for TMD and NMD BM/C^3 applications. Additionally, current efforts to merge and integrate IS&T-sponsored optimistic computing and all-optical deflection routing/distributed processing technologies are discussed.

1.0 Introduction

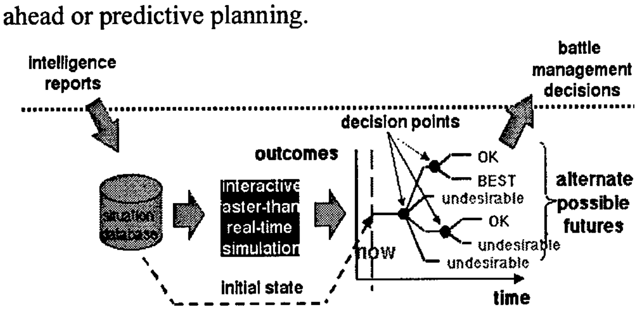
Battle management (BM) is the full-time automated process of analysis, planning, organizing, direction, coordination, and control over sensor devices and weapons. BM reflects policy, rules of engagement and operational doctrine. It is always subject to human control and override. This final attribute ensures that in any BM/C^3 system, the ultimate decision-maker will always be the human-in-control (HIC). Command and control in support of BM is the process by which the decision-maker selects among competing options in order to achieve strategic and tactical objectives; communications is the means by which those command decisions are made and executed. BM/C^3 systems provide the capability for the HIC to plan, coordinate, direct, and control weapons and sensors. Regardless of the level of automation the ultimate decision-maker will always be the

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

DTIC QUALITY INSPECTED 4

HIC. Therefore, any technology effort directed at improving the quality (timeliness, correctness, clarity, appropriateness, comprehensibility) of the data on which the HIC bases his command decisions can ultimately improve the quality of those decisions resulting in increased effectiveness. As a consequence, the current focus of BM/C^3 for NMD is the support of informed-decision making by providing the HIC with extensive decision support systems, displays, and situation awareness information. To address potential threats, BM/C^3 systems must be increasingly faster in acquisition and processing of widely-distributed multi-sensor, multi-source, multi-media data, information, and knowledge to perform BM/C^3 functions in mission-oriented tactical and strategic environments. BM/C^3 information technology research must address the information processing challenges associated with distributed information systems by providing new and innovative concepts in advanced distributed processing, high-speed communications, and automated decision support.

An example of such a system requiring innovative concepts in advanced distributed processing, high-speed communications, and automated decision support is the NMD BM/C^3 Predictive Planner, utilized during battle preplanning, plan selection, and plan evaluation processes. The predictive planner utilizes algorithms that are designed to help the HIC appreciate and understand potential battle plans and the impacts of various control mechanisms. The predictive planner provides real-time prediction of course of action (CoA) performance based on a directed battle plan. Currently, the time available for plan evaluation and assessment is constrained by the time required for look-ahead or predictive planning.



On-line Interactive Decision Aids = Rapid Situation Analysis/Planning
- **Enables more effective, efficient battle management**
- **Use in "hot" situations with live feeds containing latest intelligence info**
- **Faster-than-real-time to rapidly evaluate alternative courses of action**
- **Interactive - Allows Commander to explore space of possible futures**

Figure 1. Evaluating Alternate Possible Futures Using A Faster-Than-Real-Time On-Line Interactive Decision Aid

If the predictive planning function could be sped up significantly (10 to 100 times faster), time saved could be used to evaluate "What-If?" options on future threat launches (Figure 1). To achieve this objective techniques must be developed to minimize the time required to evaluate each possible CoA/threat pairing.

BMDO's goal is to foster growth in geographically-distributed, low-latency, fault-tolerant BM/C^3 computing via emerging technologies, such as, the Georgia Tech Time Warp and the University of Colorado's ShuffleNet "Space-Time" Deflection Routing efforts. Technology demonstrations are used to provide insight into the utility of these and related emerging technologies, as well as, offer Program Managers (PMs) with a basis for making relevant program element decisions. Under BMDO sponsorship, the US Army Space and Missile Defense Command (USASMDC) Advanced Technology Directorate (ATD) manages information technology research forming the basis for future distributed information systems. BM/C^3 information technologies must address the challenges associated with utilizing multi-sensor, multi-source, multi-media data, information, and knowledge to perform planning, control, coordination, monitoring, assessment, communication, and security in mission-oriented tactical and strategic environments. Supported IS&T and Small Business Innovative Research (SBIR) programs have the potential to significantly advance state of the art in BM/C^3 information technology. The ATD's current information technology research programs address the challenges associated with distributed information systems by providing new and innovative concepts for advanced distributed processing, high-speed communications, advanced computer security, automated decision support, and software engineering technologies.

2.0 Optimistic Parallel Computing

2.1 Overview

Optimistic simulation offers fundamental advantages over traditional conservative synchronization mechanisms. The optimistic simulation executive, GTW, is an implementation of the "virtual time" paradigm [Jefferson 1985] called the Time Warp mechanism. A generalization of the GTW mechanism and potential application are shown in Figure 2. This example shows the GTW hosted on a heterogeneous distributed (although geographically co-located) network of readily available and affordable multiprocessors and workstations, as opposed to a more expensive large-scale supercomputer.

GTW seeks to minimize the significant event processing overheads associated with the original Time Warp proposal [Das *et al.* 1994]. A major application area for this technology has been, and continues to be, the synchronization of distributed PDESs. To accomplish this, Time Warp systems, including GTW, rely on some implementation of "lookahead (peering into the future) - rollback" as the fundamental synchronization mechanism for distributed simulation objects, or as they are called in GTW, logical processes (LPs). This approach allows a distributed LP to execute based upon its own local virtual clock without regard to synchronization conflicts with other processes, i.e., optimistically. This method dramatically simplifies development of PDESs by virtually decoupling LPs and freeing the developer from process synchronization concerns. Additional advantages are gained via optimistic synchronization's shorter simulation execution times, as compared to sequential or other PDES approaches. Performance improvements, associated with allowing processes to execute optimistically generally outweigh the costs associated with occasionally "rolling back".

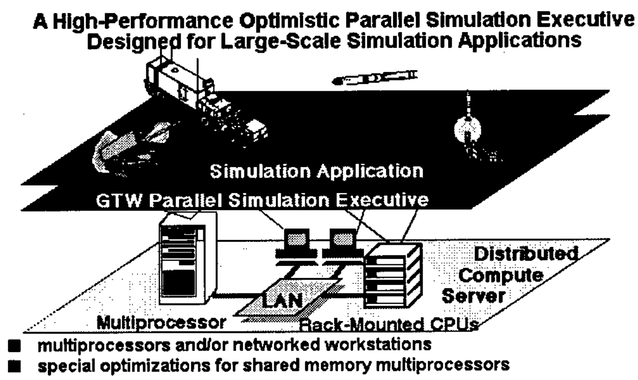


Figure 2. Generalized View of GTW Parallel Simulation Executive

The potential speedup of simulations built on the GTW executive is directly related to the number of processors, the number of events that must be eventually rolled back, processor idle time, and the overhead associated with parallel execution [Gupta *et al.* 1991; Carothers *et al.* 1994]. Innovations to the original Time Warp include adaptive optimistic synchronization protocols, fast recovery from synchronization errors, efficient memory reclamation, optimistic I/O, and load-balancing algorithms enabling background execution. These innovations yield reduced time associated with rollback and message cancellation and increased speedups in execution.

2.2 Current Research and Technology Demonstration

Under BMDO's IS&T contract DASG60-95-C-0103, monitored by the USASMDC ATD, Georgia Tech has produced new techniques and algorithms to enable efficient realization of optimistic synchronization mechanisms. Results of this research are incorporated into the GTW.

Objectives. In April 1998, a proof-of-principle (POP) technology demonstration was held to examine the technical value of GTW. IS&T goals met by the demonstration were:

- Determine the soundness of the technology developer's scientific approach,
- Measure enhancements realized in system performance through use of the new technology,
- Determine the feasibility for insertion into appropriate programs.

This demonstration focused on the applicability of the optimistic computing research, such as the GTW, to TMD and NMD BM/C^3. The demonstration showed that GTW optimistic computing technology simplifies parallelization and significantly speeds-up the execution of an existing sequential BM/C^3 discrete event system simulation. The simulation chosen for demonstration was the Theater High Altitude Area Defense (THAAD) Integrated System Effectiveness Simulation (TISES), a validated BM/C^3 simulation, using pre-canned scenarios provided by the THAAD Program. This demonstration showed that this technology provides a viable mechanism for realizing the development of a faster-than-real-time Defense Planning and Evaluation capability. In addition, it provided a relevant demonstration of the optimistic computing technology to a specific BM/C^3 data processing challenge, and to a specific problem not otherwise amenable to parallelization through traditional means. Specific technical objectives met were to prove that:

- integrating GTW with an existing large-scale simulator is feasible, using the TISES/GTW effort as a proof-of-concept;
- GTW can reduce the execution time of TISES, thus allowing the TISES to move towards becoming an on-line decision aid for use in time-critical scenarios.

Approach. The TISES is a system engineering analysis tool to support end-to-end performance evaluation of a multi-battery THAAD demonstration/validation system in a many-on-many environment. Each simulated battery consists of a battery tactical operations center (TOC), three to nine local launchers, one local radar, and connectivity to a battalion TOC. Simulation architecture is highly modular,

consisting of several detailed system segment models, including a BM/C^3 model, executing within a simulation framework. The large size of the TISES precluded parallelization of the entire simulation. Thus, demonstration focused on parallelization and speed-up of the Engagement Planning (EP) sub-module within the TISES BM/C^3 model. Using a multiprocessor configuration, a speed-up on the order of three to four times was required to be demonstrated for the parallelized TISES EP sub-module on four processors; a higher-order was required for any greater number of utilized processors.

__Performance and Efficiency Results.__ Following functional exercise of the GTW/TISES application, performance and efficiency were examined. Time Warp-relevant performance statistics showed performance objectives were met.

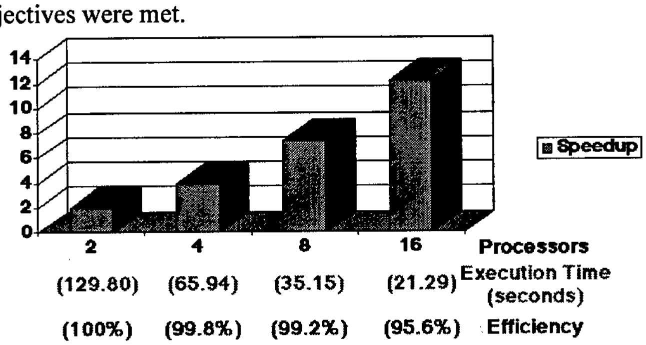


Figure 3. Performance Measurements: Using GTW and Parallelization to Speed-up Execution of a Specific Scenario—64 TOCs

For figures 3 and 4, *speed-up* equals sequential execution time divided by parallel execution time; *efficiency* is the fraction of computation performed which is *not* later rolled back. Results showed performance gains using GTW for a specific scenario. Figure 3, shows a fixed-sized problem and the addition of processors to speed-up execution. A maximum or 16 processors are shown with an efficiency maintained of 95.6 percent and a twelve-fold speedup observed over a single processor run.

Results also showed performance gains when using GTW to allow an increase in the size of a problem to be solved. Figure 4, shows a variable-sized problem, with addition of processors to speed-up execution and resultant performance gains using GTW for a specific scenario. Scale of problem size and increase in number of processors is done proportionally.

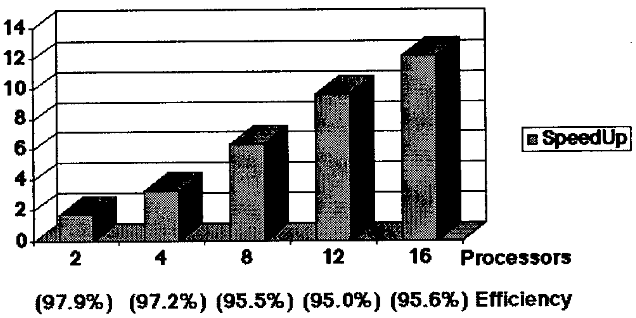


Figure 4. Performance Measurements: Using GTW and Parallelization to Increase Problem Size (Scalability)— 4 TOCs per Processor

__Research Applicability.__ Georgia Tech's Optimistic Computing research has produced new techniques and algorithms, which enable efficient realization of optimistic synchronization mechanisms. As incorporated into the high-performance optimistic simulation executive, GTW, optimistic computing technology can simplify parallelization and significantly speed-up the execution of an existing sequential discrete event system simulation. Use of optimistic parallel simulation technologies in the reengineering of existing sequential discrete event simulations to PDESs, and application of such technologies in the development of new PDESs merits serious consideration.

__Future Directions.__ The natural progression of this research is to extend it toward the development and demonstration of an optimistic simulation based real-time defense planning and evaluation capability to support NMD BM/C^3 lookahead and predictive battle planning objectives [McFee *et al.* 1998]. In addition, the ATD is investigating other potential applications to NMD data processing challenges.

__3.0 ShuffleNet "Space-Time" Deflection Routing__

__3.1 Overview__

For many military situations a distributed and robust processing system is essential. Requirements of such a geographically distributed military system might include:

- 40 or more Gigabits/second optical data links from 10 to 100 Km,
- 10 or more Gigabits/second laser data links,
- Radio-frequency links supporting surface to space connectivity, and,
- Non-line of sight communications at near-speed of light.

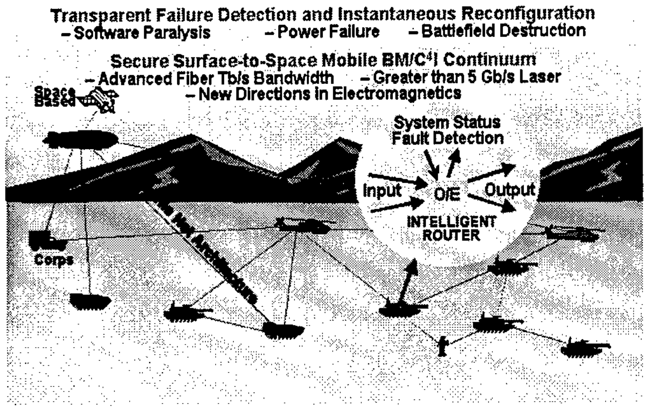


Figure 5. Use of Intelligent Router Application in a Geographically Distributed Military System: Non-Line of Sight Platform Communications at Near Speed of Light

Figure 5 depicts an example use for an intelligent all-optical router application in such a geographically distributed engagement environment with non-line of sight communications required at or near the speed of light.

3.2 Current Research and Technology Demonstration

Under BMDO's IS&T contract DASG60-95-C-0112, monitored by the USASMDC ATD, the University of Colorado, at Boulder, is performing research into all-optical distributed processing. Hardware, firmware, and software are currently under development in Boulder, with application integration and demonstration to be performed at the USASMDC Advanced Research Center (ARC), Huntsville, Alabama. To date, demonstrated capabilities include:

- POP 2X2 deflection routing (enabling scalable systems),
- Software POP from the highest (application) level to the lowest (network firmware) level,
- Support for a realistic distributed application spread across both processes and processors,
- Scalability in both processing power and processor separation with the limits imposed by available processing power and network hardware.

Objectives. The objective of the University of Colorado research is to develop a system possessing network hardware and software message passing interfaces supporting near speed of light message routing and sub-millisecond system reconfiguration from component "failure" messages. Such a system will provide

- Physical robustness,
- Scalable processing power, with upgrade though spares possible, incremental growth, distributed ownership, commodity parts,
- Interfaces that allow retrofitting to stay on a very rapid upward *commercial* trajectory.

Approach. In constructing this system, the research approach pursued is to adapt low-latency switching and message protocols and techniques originally developed for geographically-local parallel supercomputers. Newer technologies, especially high-speed optical links, coupled with enhanced protocols and topologies are being employed. In particular, a variation of deflection routing and ShuffleNet inter-connections are utilized. In the process, a new variation on deflection-routing called *two-space, two-time* (2S2T) was developed [Hayes *et al.* 1997]. Extensive mathematical analysis not only verifies the refined switching and protocol concepts, but indicates that such a robust, fault tolerant, widely-distributed militarized system can be constructed with commercial-off-the-shelf (COTS) components at *one-fifth the supercomputer cost.* The underlying feature for implementing this concept is a new six layer board, Figure 6, developed by VeriBest, Incorporated. The board incorporates the theoretical concepts developed by the University of Colorado with the practical reality of low-cost, readily available commercial components.

Effort Progress. Efforts have resulted in the construction of a four-node ShuffleNet prototype machine constructed from four COTS workstations interconnected with Myrinet Portable Computer Interface (PCI) cards and the Myrinet switch. The Message Passing Interface (MPI) standard is being used for interprocessor communication. Statistics for interconnect performance for Myrinet and Ethernet data transport have been demonstrated. A demonstration of this configuration is planned for July 1998 with a four-processor POP application, a computationally-intensive distributed radar signature simulation developed by COLSA Corporation; this application is now using MPI for interprocess communication over the Myrinet interconnections between multiple processors. Follow-on efforts will begin to port the GTW optimistic computing executive to this configuration for a follow-on demonstration. A follow-on algorithm for fast electromagnetic (EM) propagation will be used for the follow-on demonstration to be set up on the ShuffleNet configuration. This non-standard finite differences program can serve as part of a third demonstration for late 1998 applied to a specific application of USASMDC interest, emphasizing radar returns from a highly fragmented, irregularly-shaped group of objects. Using this application,

techniques can be determined to quickly separate intact warheads from intentional or unintentional clutter from many small, irregular, reflective nearby objects.

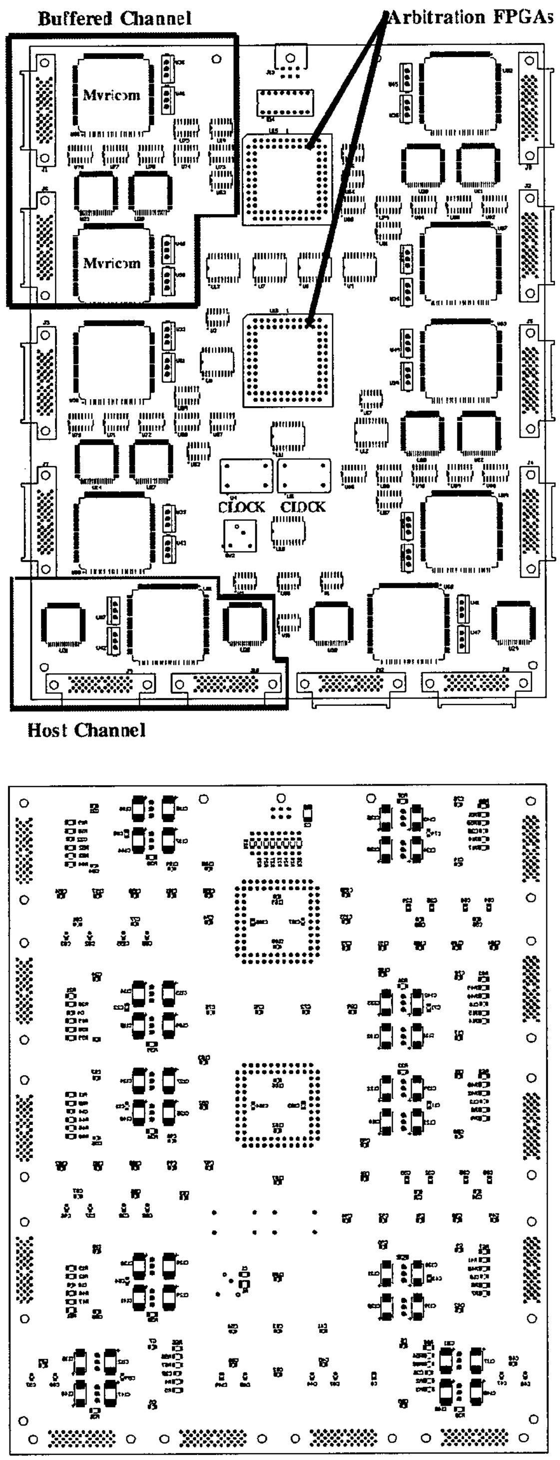


Figure 6. Top and Bottom View: Myrinet Arbitration Board

__Research Applicability.__ When ShuffleNet "Space-Time" deflection-routing technology is used the result will be considerable cost savings. Based upon current cost-calculations, the direct cost savings by using COTS workstations instead of supercomputers is estimated by the authors to be at least $12M in hardware, software and maintenance for each installation site. Additionally, by linking current computing hardware, laboratories, and facilities with these technologies, an estimated $10M may be saved per facility by leveraging existing assets. When combined with optimistic parallel computing and OPDES techniques, the utilization of these technologies in support of test and evaluation requirements through improved simulation performance may yield even higher savings and broader utility.

__Future Directions.__ As the IS&T optimistic simulation effort is also concerned with high-performance simulation techniques that utilize COTS "cluster supercomputers" (i.e., networked workstations and multiprocessors) to perform faster-than-real-time execution of missile defense simulations, it is logical and practical to extend this research to enable optimistic parallel computing technology to reside on optical geographically-distributed hardware platforms. Addition of optimistic simulation technology will offer even greater exploitation of concurrent execution, simpler simulation model development, and greater performance robustness as compared to so-called conservative parallel/distributed discrete event simulation approaches. This technology in combination with the ongoing ATD research dealing with developing innovative techniques for networking distributed COTS workstations via all-optical "ShuffleNet" networks utilizing 2S2T routing architectures provides essential infrastructure to meet future BM technology objectives. The USASMDC ATD Distributed Computing Program will merge BMDO IS&T research in optimistic simulation techniques and optical multiprocessor interconnects to develop a low-cost distributed computing capability to support a variety of BM applications including NMD and TMD mission pre-planning and real-time adaptive planning.

4.0 Conclusions

The goal of the BMDO IS&T Distributed Computing and Simulation Program is to merge research in optical multiprocessor interconnects, optimistic computing techniques, advanced computer security, automated decision support and other technologies to provide low-cost, distributed adaptive "supercomputer" capabilities for a

variety of BM/C^3 applications that range from faster than real-time mission planning to sensor fusion. In addition, this technology program provides essential infrastructure for such efforts as the National Virtual Distributed Hardware-in-the-loop TestBed (VDHTB) to demonstrate a more robust pre-flight distributed test capability. As an initial step, a small scale BM/C^3 testbed has been established by the USASMDC to provide a laboratory environment in which both researchers and technology insertion agents can explore fundamental principles regarding shared distributed BM decision-making. The laboratory will allow for a synergistic insertion/transition of the above emerging ATD technologies to the warfighter, in such a way as not only to provide increased capability, but also to produce maximum effectiveness. Additionally, within this environment, efforts to merge and integrate IS&T-sponsored optimistic computing and all-optical deflection routing/distributed processing technologies may be explored.

References

Carothers, C., R. Fujimoto, Y. Lin and P. England. 1994. "Distributed Simulation of Large-Scale PCS Networks." In *Proceedings of the MASCOTS Conference* (Raleigh, NC, Jan). 1-6.

Das, S., R. Fujimoto, K. Panesar, D. Allison, and M. Hybinette. 1994. "GTW: A Time Warp System for Shared Memory Multiprocessors." *In Proceedings of the 1994 Winter Simulation Conference* (Orlando, FL, Dec.). 1332-1339.

Gupta, A., F. Akyildiz, R. Fujimoto. 1991. "Performance Analysis of Time Warp with Multiple Homogeneous Processors." *IEEE Transactions on Software Engineering 17*, no. 10 (October). 1013-1027.

Hayes, J. L., C. R. Green, I. W. Merritt, J. C. Hayes, J. K. McFee, Jr. 1997. "Information Processing Technologies for BM/C^3 Applications." In *Proceedings of the American Institute of Aeronautics and Astronautics (AIAA) Defense and Space Programs Conference* (Huntsville, AL, Sept. 23-25). AIAA. 225-231.

Jefferson, D. 1985. "Virtual Time." *ACM Transactions on Programming Language and Systems 7,* no. 3 (July). 404-425.

McFee, J., K. Pathak, J. Shaw, M. Weise. 1998. "Application of Optimistic PDES Techniques to Performing Real-Time Predictive Battle Planning for National Missile Defense." In *Proceedings of The Society for Computer Simulation International 1998 Summer Computer Simulation Conference.*